DEVELOPMENT OF RESTRAINT SYSTEMS WITH CONSIDERATIONS FOR EQUALITY OF INJURY RISK

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ABSTRACT

Occupant restraint system development continues to evolve as new regulations and consumer demand drive more complex solutions. Traditional seat belt and airbag designs are giving way to more intelligent systems that respond to crash and occupant conditions. In regulated vehicle compliance safety tests, occupant performance is usually judged against injury criteria that differ with respect to occupant size. While for a given test, two different occupant sizes may give results that pass the criteria, their probabilities of injury for a given body region may not be equal. It may be possible to change restraint configurations that not only demonstrate compliance to recognized injury criteria for a given occupant, but additionally demonstrate that for a given crash mode, an equal probability of injury exists for all body regions of a range of adult occupant sizes. This paper will discuss a computer modeling approach devised to analyze a particular vehicle environment and range of occupant sizes. A design of experiments was carried out that adjusted parameters of the restraint system including seat belt pretensioners, load limits, and various airbag components. For each analysis, the probability of injury by body region and occupant were compared to find the set of components that comprise a system to give equal probability of injury for each body region for each occupant. Results of the design of experiments, statistical analysis and impact on restraint system development will be discussed. This paper documents a new approach to restraint system development as it looks beyond specific injury criteria to injury risk comparisons.

INTRODUCTION

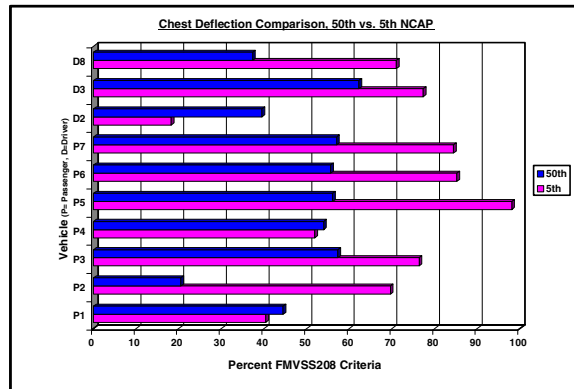### Previous Studies on Adaptive Restraints

Adomeit quotes in a previous report "The more loads differ within the range of injury criteria under different test conditions or under real world accident conditions – or even exceed injury criteria in certain circumstances – the more we need active restraint system adjustments related to input parameters: in other words, adaptation of restraint system" (1). These words have motivated a number of studies to explore the adaptability of restraint systems to the occupant and vehicle crash environment. Bendjellal et al(2) described a "programmed restraint system" that incorporated airbag pressure and seatbelt force limiters to reduce occupant injury criteria relative to standard belt/bag systems. Their aim was to reduce thoracic loads induced in occupants for different crash modes. Foret-Bruno et al (3) determined occupant thoracic injury risk by age based on analysis of crashes of vehicles equipped with this programmed restraint system. A 4kN shoulder belt load limit was recommended for all occupants based on this analysis, but made no mention of occupant size. Miller and Maripudi (4) performed a computer modeling study to determine restraint parameters required for 5th percentile female, 50th percentile male, and 95th percentile male dummy models. By adjusting belt load limit and airbag venting properties for these 3 occupants in normally seated positions, they could determine the optimal requirements for those restraint parameters that resulted in the lowest injury criteria for each dummy size. That study, however, did not make any adjustments to the inflator performance during the simulation.
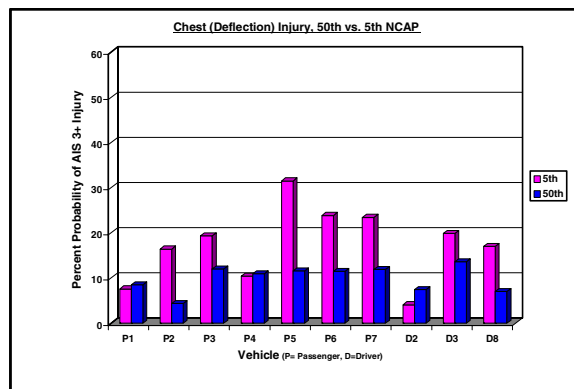
Happee et al (5) showed that by varying occupant size through scaling techniques, outside the standard dummy model sizes, large variations in injury criteria could occur as a result of different seating positions for the same restraint systems. Cuerden et al (6) proposed that a 25-45% reduction of AIS 2 and 3 injuries could be achieved with adaptive restraint systems compared to belted only occupants. His analysis relied on a hypothetical injury reduction matrix applied to set of field injuries with known severity for a given occupant type. Breed (7) hypothesized that airbag inflation rate as well as gas discharge from the airbag could be controlled relative to occupant position and morphology if the ability to determine that position and morphology existed. This follows the Happee study, but no test or model data is given. These early studies suggested the need to have a restraint system that adjusted to the

occupant size for a large range of crash conditions and occupant size.

Dummy performance by size

In its efforts to provide regulations aimed at more of the adult population, NHTSA added the 5th percentile female to the passive safety requirement and has proposed adding the same dummy to the belted, 35mph (56kph) NCAP barrier crash that will also phase into the passive safety requirement (8). In its own testing of 18 vehicles with non-adaptive restraint systems, NHTSA has found 6 vehicles that exceeded injury value limits for 5th percentile female drivers in the areas of head, chest, and/or neck regions while the 50th percentile male driver did not exceed criteria. In the other 12 vehicles, it was found that "the overall injury values for the 5th percentile adult female driver dummies in [the tested] vehicles were somewhat higher than the values for the 50th percentile driver dummies tested in the same vehicle (9)." The neck area was usually the highest value difference.

In a more detailed study (10), NHTSA reported results from 5 paired vehicle crash tests where either the 5th female (full forward) or 50th male (mid-track) was the driver and passenger occupant. The results showed that 5th female driver and passengers typically had higher chest acceleration and neck injury criteria (Nij) values than the 50th male driver and passenger in the same vehicle. HIC values did not differ significantly between dummy sizes. Maltese et al (11) ran 35 vehicle tests with mostly unbelted 5th and 50th percentile dummies and saw similar increase neck injury criteria for the 5th percentile female dummy regardless of vehicle type or crash severity.

An Analysis of NCAP Results for 5th/50th

In an effort to better understand the differences between 5th and 50th percentile dummy responses, data from three different driver and seven different passenger NCAP tests or mathematical models was collected relative to 5th or 50th dummy response in the same vehicle sled test or model. NCAP star ratings based on HIC and chest acceleration (Gs) were compared for the same test or model and are shown in Figure 1. In every case, the 5th percentile female chest G's increased relative to the 50th percentile male while HIC exhibited little difference, or in some cases, slightly improved. Chest deflection in the 5th percentile female showed increases in 5 of the passenger and 2 of the driver tests or models,

however all values were below the FMVSS 208 injury criteria value for chest deflection (Figure 2).

Taking the analysis further, the injury probabilities for an AIS 3+ chest injury using these chest deflections were compared between 5th and 50th dummy sizes (Figure 3). The scale factors from published data by Mertz et al (12) were used to calculate the probabilities. The comparisons of injury probabilities reveal that the likelihood of an AIS 3+ chest injury (e.g.: multiple rib fractures) was significantly higher for the 5th female in all the cases where the injury criteria was higher. In one case, the risk of chest injury was 3 times higher for a 5th female even though the injury criteria increased by 30% compared to the 50th male occupant.

It is the response to the crash loads among different occupant sizes in a given crash configuration that may need to be addressed with an adaptive restraint system. As the issues of addressing the restraint requirements for the smaller occupant arose as a result of the airbag-induced injury, NHTSA added the small female crash dummy to its passive restraint certification requirements for passenger vehicles. It may not be enough, however, to accept the fact that an injury criteria for a 50th %ile male may translate into a 15% probability of injury, while a 5th %ile female is subject to a 30% probability of injury for the same crash configuration and restraint system.

Figure 1. Driver and/or passenger occupant response for 5th %ile female (triangle) and 50th %ile male (circle) for various driver and passenger vehicle restraint systems.

The possibility to equalize the injury probability for the two occupant sizes by body region in a given crash configuration forms the basis for the current study. Identifying restraint system parameters that can be adjusted to the occupant while maintaining a balanced or equal probability of injury and

complying with existing injury criteria can only be solved using computer techniques building on the biomechanics data existing in the literature.

Figure 2. Driver and/or passenger occupant chest deflection response (5th %ile female in pink and 50th %ile male in blue) for various driver and passenger vehicle restraint systems.

Figure 3. Driver and/or passenger occupant chest injury probability (based on deflection response) for 5th %ile female and 50th %ile male) for various driver and passenger vehicle restraint systems.

METHODS

The basic premise for the analysis was a full-factorial Design of Experiments (DOE) on 5 restraint system parameters. The restraint parameters are shown in Table 1. Pretensioners A and B are single pretensioners while C and D are dual pretensioner seat belt systems.

Table 1.
Restraint Parameter Levels Used in Analysis

Variable	Levels
Seat Belt Pretensioner	Types A,B,C,D
Seat Belt Load Limiter	Low, Medium, High
Seat Belt Payout	Low, Medium, High
Inflatable Knee Bolster	On/Off
Active Airbag Vent	On/Off

Four MADYMO (13) base models were created for the purpose of this study using a sport utility vehicle configuration. The first was modified from an existing 50th passenger NCAP model by adding pretensioner Type A and by adding replaceable parameters for turning pretensioners and active venting on or off based on parameters in the matrix. The first file also called out the proper load limiter functions based on peak and payout of the load limiter (9 combinations). The second file for the 50th male has an added inflatable knee bolster. The third and fourth input files were created from the first two files by repositioning the seat and replacing the 50th male dummy with a 5th female dummy. The iSight (14) program was used to generate a 72 run matrix with the remaining input parameters (load limit peak and payout, active vent, and pretensioner configuration). It was set up to make preliminary calculations to get the required replaceable parameters for each run, make the proper substitutions in all four input files, submit the jobs to the MADYMO solver in parallel (up to 3 jobs could be run simultaneously), extract desired data from the output files after completion, perform calculations of injury probabilities from the output, perform combined calculations after all four runs for each iteration finished, then start over with the next line of the matrix and continue until all 72 lines of the matrix were done. When the runs were complete, a complete results file was generated from all 288 runs (72 parameter combinations times 4 input files) to use for analysis with the input parameters, the results, and the calculations.

Probabilities for AIS 3 and greater head, chest and neck and AIS 2 (and greater) lower extremity injury were derived from published charts by NHTSA (15,16) and Mertz et al (12,17,18). HIC was used as the head injury measure, while absolute chest compression and neck tension were used as injury measures for the chest and neck respectively.

The peak injury values taken from the MADYMO output file and compiled in the results file database of the 288 runs were compared to the published injury probability functions for an AIS 3+ injury. An RMS (root mean squared) value was calculated from the

head, chest, and neck injury probabilities (square root of the sum of the squares). The rationale for using the RMS value will be discussed later. Each run was ranked in terms of its RMS value and the associated restraint parameters. The MiniTab Statistical software was used to process the data to obtain relevant statistical measures, and provide main effects plots, and plot the data for each run with respect to injury probability and various restraint parameters.

RESULTS

A plot of all 288 runs for the SUV model demonstrated the ability of the analysis to show differences (Figure 4). It can be seen immediately from the figure that the probability for injury of the various body region is low for this model. Neck injury
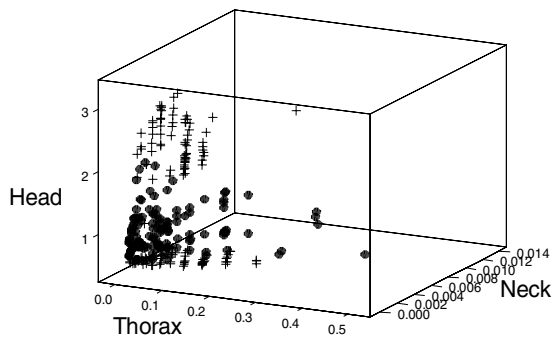
Figure 4. Percent probability of AIS 3+ head, neck or thorax injury for 5th percentile female (+) or 50th percentile male (●) for each of parameter run of the DOE matrix for the SUV model.

shows the lowest probability followed by thorax and head with increased probabilities respectively. The 50th percentile male dummy shows a tight single cluster of results with a small distribution of outlier results. The 5th female dummy shows two clusters of results with the second cluster showing higher head injury risk than the first cluster. Further examination of the second cluster of results indicates that all of those cases did not have the active venting feature in the airbag module.
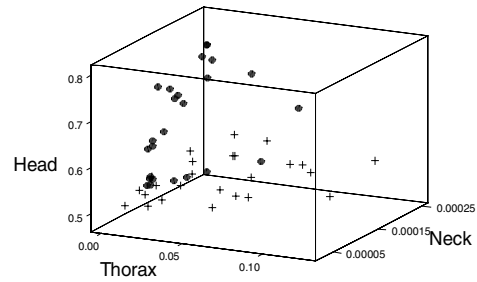
Figure 5. Top 25 restraint systems in terms of percent probability of AIS 3+ head, neck or thorax injury for 5th percentile female (+) or 50th percentile male (●) for each of parameter run of the DOE matrix for the SUV model.

Rejecting those cases, the top 25 systems for both 5th percentile male and 50th percentile male are shown in Figure 5. A tabulation of those cases was made from lowest RMS score to highest RMS score. The top 5 systems for each occupant are shown in Table 2 in terms of the combined injury risk defined as the RMS value for the three injury criteria. The table shows the system components for those top 5 systems for each occupant. As previously stated, the active venting was present in all systems for the 5th as well as the 50th. All systems included the lowest load limiter used in the analysis, however, all the 5th percentile dummy systems used the high payout option. A mix of pretensioners is also present with the 50th systems dominated by the more complex pretensioner types. No 50th system in the top 5 required a knee bag.

Table 2.
Restraint System Definition for Top 5 Scoring Systems According to Occupant Size. (PRET=Pretensioner, LL=Load Limit, PAY=Webbing Payout, AV= Active Vent, KB= Knee Bag)

OCC	RMS	PRET	LL	PAY	AV	KB
5th	.489	A	LOW	HIGH	Y	N
	.499	B	LOW	HIGH	Y	N
	.507	D	LOW	HIGH	Y	Y
	.513	B	LOW	HIGH	Y	Y
	.515	A	LOW	HIGH	Y	Y
50th	.563	C	LOW	LOW	Y	N
	.567	D	LOW	LOW	Y	N
	.572	D	LOW	MED	Y	N
	.576	A	LOW	MED	Y	N
	.577	C	LOW	MED	Y	N
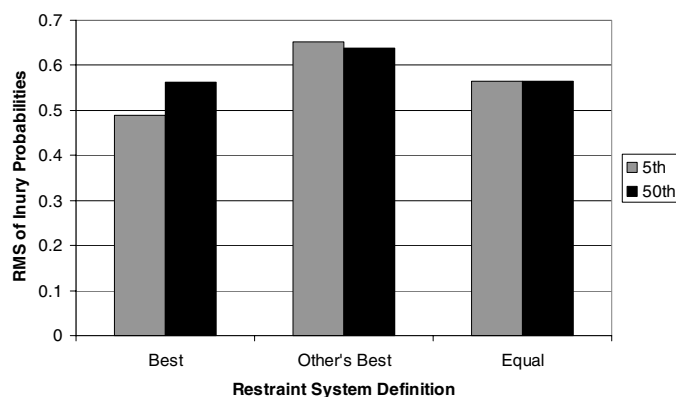
Figure 6. RMS comparison for 5th and 50th in terms of best system for itself, the other dummy's best system, and system for equal probability.

Table 3.
Restraint System Definition for Equal RMS Probability of Injury for 5th Percentile Female and 50th Percentile Male Dummy.
(PRET=Pretensioner, LL=Load Limit, PAY=Webbing Payout, AV= Active Vent, KB= Knee Bag)

OCC	RMS	PRET	LL	PAY	AV	KB
5th	.565	A	MED	HIGH	Y	N
50th	.565	C	LOW	LOW	Y	N

The 5th percentile dummy's best system was the 13th best system for the 50th (out of 144), while the 50th's best system was the 38th best system for the 5th.

When comparing the result of using the other dummy's best system in the simulation, i.e., using the 50th's best system in the 5th's model and vice versa, the result is shown in Figure 6. Both dummies RMS probabilities increase relative to its best system. In terms of actual injury criteria, the HIC and chest compressions can increase by as much as 30% for these simulations. By picking the systems that result in equal probability for both dummy models, there is no degradation for the 50th percentile dummy (RMS changed 0.002), but a more substantial increase for the 5th percentile dummy (from 0.489 to 0.565). When looking at the injury criteria, this result translates into a 35 point increase in HIC and 3mm increase in chest compression. Both systems for equal probability favor no knee bag and the presence of active venting while none of the seat belt characteristics are same in either system.

DISCUSSION

The efforts to define adaptive restraint systems have been discussed in both the media and scientific publications (1,7). It is generally acknowledged that these systems would have a beneficial effect on occupant response as the components of the restraint system could be adjusted to the occupant size, position, crash configuration, etc (6,19,20). It becomes prohibitive, in terms of cost, to test all possible combinations of test and restraint system conditions, thus leading to computer methods to analyze the system. Iyota and Ishikawa (21) demonstrated a modeling method to assess injury risk for 5th, 50th and 95th percentile dummies based on load limiting at the seat belt retractor and airbag vent hole size. Using the NHTSA derived combined head (HIC) and chest injury (chest G) injury probability calculation, they defined the parameters of the two variables that would give a similar injury probability for all three occupant sizes.

The current study uses a similar modeling approach, but uses three injury parameters (HIC, chest compression, and neck tension) and more restraint system components to define the restraint system that results in equal probability of injury risk by body region for the 5th percentile female and 50th percentile male dummies. Defining injury risk is not a new issue as both governmental (US-NCAP) and consumer testing agencies (IIHS and EuroNCAP) express their injury criteria and levels of performance based on risk of injury to various body regions (16,22,23). However, the probabilities for ratings are not balanced. For example, the IIHS criteria for an acceptable-marginal vehicle rating based on head (HIC), Chest (chest compression) and Neck (neck tension) injury criteria would give an unequal probability of AIS3+ injury for head (5.6%), neck (4.5%) and chest (45%) for a 50th percentile male dummy. The approach described in this paper selects restraint system parameters that result in an equal probability of injury for each dummy body region as well as for each dummy size. In this manner, the overall system design can be achieved that satisfies the equal probability goal. The system for the 5th female and 50th male that gave the best result for each dummy would not have been the best system for the other dummy. By defining an equal probability, it was possible to find the appropriate system components. In the current simulation, the HIC, chest compression, and neck tension probabilities remained equal as the RMS number indicates. Also, it is assumed that the injury severities considered for each body region were equal as determined by their AIS value. That is, an AIS 3 head injury carried the

same severity as an AIS 3 chest injury.   While NHTSA sums the head and chest injury probabilities in their NCAP star rating, this report calculated an RMS value for head, neck and chest that provided a method for ranking the various systems analyzed.

There may be challenges in achieving this goal of equal injury probability as the restraint system parameters are adjusted. System designs may not be possible based on the components selected in the analysis. In its response to the NHTSA NPRM on addition of 5th female to NCAP test conditions, General Motors cited that the performance of the 5th percentile female dummy "improved with higher output/more aggressive airbags"(24). This can have negative consequences on other test conditions such as unbelted occupants and out-of-position occupants. This was discussed by Trosseille et al (25) who analyzed the out-of-position risk of an optimized thorax restraint system comprised of a pretensioner, load limiter and airbag system.

The current analysis did not take into account airbag inflator output, airbag shape, or vent hole size, all of which may have an effect on the occupant response. The active venting feature used in the analysis, provides for a controlled release of airbag gas that was shown to have a positive effect on the occupant response when used. It is the process in this study that needs to be highlighted rather than the results since an analysis comprised of thousands of simulations is possible as the number of parameters increases. Regardless of parameters used, all results will lead to an equalization of injury probability by occupant size and occupant body region rather than just considering the basic injury reference values. This analysis does not consider effects of age on likelihood of injury (26) nor does it consider that the system definition to achieve equal probability from one vehicle may be different than that of another vehicle. On a higher level of any injury risk to any occupant, Kullgren et al (27) demonstrated that the injury risk functions differ from vehicle to vehicle for a given crash severity. As the future development of restraint systems continues, this new technique of establishing equal injury probability for all occupant sizes, while maintaining margins for acceptable injury criteria, may lead to further improvements in vehicle safety.

ACKNOWLEDGEMENTS

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